ARCTIC MIXED LAYER DYNAMICS

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LONG TERM GOALS

Our long term goal is to understand the dynamic and thermodynamic processes causing changes in the velocity and density structure of the upper Arctic Ocean. For example we seek to understand the heat and mass balance of the mixed layer, and the dynamics of internal waves in the Arctic.

OBJECTIVES

Our long term goals have taken on new significance considering recent changes in the Arctic Ocean hydrography. The results of several expeditions in the 1990's indicate the upper Arctic Ocean is increasingly dominated by the Atlantic Water. The salinity of the upper 200 m of the Makarov Basin has increased by over 2.5 o/oo. A warm core of Atlantic Water now lies over the Lomonosov Ridge and the halocline is thinning. Two of our immediate objectives have been to determine if the change is a significant departure from the historical climatology, and what is the role of upper ocean processes in the change. In connection with this we are contributing to the historical database with data gathered in a variety of programs, most notably our oceanographic buoy program. We also continue to explore the nuances of lead convection by analyzing data collected with our Autonomous Conductivity Temperature Vehicle (ACTV) during the ONR Lead Experiment (LeadEx).

APPROACH

We have developed and use a variety of techniques in our analyses. Standard hydrographic analysis techniques are used with the Submarine SCience ICe EXperiment (SCICEX) '93 CTD data, but we have developed graphical techniques that show the three dimensional structure of data gathered over the whole central basin. The special analysis of the buoy data takes advantage of the buoy cable motion to improve vertical resolution. In analyzing the ACTV data we determine the spatial variability of temperature and salinity by combining data from the onboard temperature and conductivity sensors and position data from our acoustic tracking range. We use techniques for estimating vertical salt and heat flux based on both direct turbulent flux calculation and an inertial dissipation method. In our work on leads we have maintained close ties with the modeling efforts of Miles McPhee and David Smith in order to interpret the experimental results.

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ACCOMPLISHMENTS

The SCICEX '93 hydrographic data has been further refined, and compared to historical Russian data. Our earlier work with the SCICEX data reveal that there was a significant shift in the circulation of the upper Arctic Ocean in 1993. The shift is substantial relative to the Russian climatology by Gorshkov (1983). We have also compared the upper ocean circulation with atmospheric pressure and ice drift data and find the shift is related to a change in the annual mean ice drift and atmospheric pressure field; the ocean, ice, and atmospheric patterns all show a counterclockwise shift relative to climatology. Consequently, we believe the change in ocean circulation may be driven by a change in atmospheric forcing. A paper on SCICEX '93 (Morison et al., 1997) was submitted to *Deep Sea Research* and is in press.

In the last year, after completing the SCICEX '93 paper, we became involved with the preparation of the Joint U.S.-Russian Atlas of the Arctic Ocean: Winter Period (EWG, 1997; Gore and Belt, 1997). We describe our involvement below, but it is appropriate to compare the results to SCICEX '93 here. The Atlas climatology is based on many Russian aircraft surveys, ice camps, and cruises conducted from the late 1930s to the late 1980s. The comparison of the SCICEX '93 data from the USS PARGO with the new Atlas shows evidence of the change in Arctic Ocean hydrography in great detail.

We have been working to organize a multi-disciplinary, multi-agency study involving measurements, analysis, and modeling in order to understand the large changes currently under way. As a first step we have circulated an Open Letter Describing a Program for a Study of Arctic Change and have proposed to the National Science Foundation a workshop on the subject. The Open Letter has been endorsed by an international group of nearly 50 scientists and the Arctic Systems Science - Ocean Atmosphere Ice Interaction (ARCSS-OAII) Steering Committee, and the workshop is being held in November of 1997.

We continued to develop new methods for processing data from the hydrographic buoys we have deployed in the Arctic Ocean since 1985 with NAVOCEANO and ONR support. We have made improvements in the method of applying the parametric fitting scheme (Steele and Morison, 1992) to the hydrographic buoy data by reducing the number of fit parameters. This increases statistical significance while keeping the critical features describing the water column structure. We have also processed the buoy data in a different way to prepare it for a new Joint U.S.-Russian Summer Atlas of the Arctic Ocean. The buoy data is the U.S. contribution of restricted data under the Gore-Chernomyrdin Agreement. NAVOCEANO sent buoy data to the Arctic and Antarctic Research Institute (AARI) in St. Petersburg, Russia, for inclusion in the Winter Atlas (EWG, 1997), but it was not in a suitable form and in time for inclusion. We performed additional quality control checks and averaged the complete data set into 10-day, 10-meter-depth bins. These steps provided virtual hydrocasts that fit naturally into the data processing system used by AARI. Buoy data from all seasons will be included in the forthcoming Summer Atlas, but the buoy data are especially important for the gridded summer fields because they provide virtually the only information for the central Arctic in summer.

The analysis of the LeadEx Autonomous Conductivity Temperature Vehicle (ACTV) data has continued to be fruitful. Working with Miles McPhee, we have developed two new techniques for estimating turbulent heat and salt flux from ACTV measurements of temperature and salinity. These techniques agree with results of our direct method using the motion of the vehicle to estimate vertical water velocity. The measurements have given us a new understanding of how surface flux, stress driven mixing, and lead geometry determine the pattern of lead convection. A paper describing these results (Morison and McPhee, 1997) was submitted and is in press. Working with

David C. Smith IV we revised a 2-dimensional, nonhydrostatic lead model. The simulations show good agreement with our experimental results, and a paper on the results has been revised, accepted and is in press (Smith and Morison, 1997).

SCIENTIFIC TECHNICAL RESULTS

The SCICEX data reveal that there was a significant shift in the circulation of the upper Arctic Ocean in the early 1990s. The shift is substantial relative to the Russian climatology. Comparison of the PARGO salinity data and the salinity from the new Atlas (EWG, 1997) interpolated to the cruise track of the PARGO shows the front between the saltier surface waters of the eastern arctic and fresher western arctic waters has shifted about 55° of longitude across the Makarov Basin. The presence of Atlantic derived water in the basin has increased. The surface salinity in the Makarov has increased 2.5 o/oo, a change comparable to the variation over the whole sea surface.

Comparison of the PARGO temperatures and temperatures from the Atlas interpolated to the cruise track of the PARGO reveal a new warm core of Atlantic Water over the Lomonosov Ridge. The maximum temperature is over 1°C warmer than in the past. Furthermore the Atlantic Water is shallower than in the past so the temperature is over 2° greater at 200 m. A less intense warm core appears over the Mendeleyev Ridge and there is a general warming in the Makarov Basin centered at around a depth of 200 m. These observations reinforce the idea that Atlantic Water has intruded across the whole Makarov Basin. Decadal statistics from the Atlas indicate this change is greater than the normal variability. The shoaling of the Atlantic Water also suggests the halocline, which isolates the surface from the warm Atlantic Water (Steele et al., 1995), is growing thinner. Does this presage a catastrophic melting of sea ice, or is it merely part of a normal decadal-scale fluctuation? Only further study will tell. Also, the extent of the Bering Sea Water temperature maximum has retreated behind the advancing Atlantic Water front. Results from other cruises are consistent with SCICEX '93 and suggest the change in conditions started around 1990. The cruise of the HENRY LARSEN in 1993 (Carmack et al., 1995; McLaughlin et al., 1996) showed the warming over the Mendeleyev Ridge. The Arctic Ocean Section (AOS) in 1994 (Carmack, et al., 1997) found the shift in the salinity front and warm cores of Atlantic Water over each of the major ridges. The temperature and salinity sections from the SCICEX '95 cruise of the USS CAVALLA (M. Steele, personal communication, 1997) show a frontal shift consistent with the pattern of SCICEX '93 and AOS.

Examination of drifting buoy results of the International Arctic Buoy Program suggests the ocean change is related to a change in the annual mean ice drift and atmospheric pressure field; the ocean, ice, and atmospheric patterns all show a counterclockwise shift relative to climatology. Consequently, we believe the change in ocean circulation is driven by a change in atmospheric forcing. The wind forcing drives the circulation change by Ekman pumping and subsequent baroclinic adjustment. The connection with lower latitude processes may be substantial.

The LeadEx ACTV results illustrate how the convection pattern varies with lead width. Convection deepens across the lead at a rate proportional to the turbulent velocity scale. Under a wide lead the convection layer grows to the depth of the mixed layer after traveling downstream only a small fraction of the distance across the lead. Therefore, most of the lead may be dominated by convection. Conversely the convective layer may not develop completely under a narrow lead. The convection is only seen in a wedge near the surface. In either case there appears to be enhancement of flux near the downstream edge due to the horizontal density gradient and the flow around the thick ice at the lead edge.

IMPACT FOR SCIENCE AND SYSTEMS APPLICATIONS

It is of utmost importance that the changes in the Arctic Ocean be studied in detail. They may represent a decadal-scale change or the start of a longer term shift. In either case examining the evolution of the changes over time will likely tell us much about the interplay of the Arctic with the rest of the globe. The Study of Arctic Change has relevance to the Navy because it involves significant changes in the upper ocean and coastal areas. These are areas important for naval operations, and it is here that oceanographic conditions are most likely to be different in the future than when examined heavily in the 1980s by the Navy. The Arctic change may be even more important for its effect on the northern sea route. Other nations, notably Japan and Russia are examining the potential of the northern sea route for trade. If the Arctic change affects navigability of the northern sea route, this may change shipping patterns between Asia and northern Europe and the strategic significance of the Arctic Ocean.

TRANSITIONS

Vehicles like the ACTV and the analysis method we are developing could be used militarily. Such AUVs could make clandestine surveys of littoral areas. The method of extracting information on water motion from vehicle motion would have application in determining the wave energy in areas of planned amphibious assault. The technique may also find application as a non-acoustic detection and tracking tool. This would find application in "smart" and acoustically quiet weapons that could detect the wakes of vessels and follow them. Torpedoes using the technique in real time could conceivably follow turbulent ship wakes to their targets.

RELATED PROJECTS

Working with a number of other oceanographers we hope to start a multi-agency effort to track the Arctic Ocean changes observed in the SCICEX and other data. So far we are calling this the Study of Arctic Change. As an outgrowth of our LeadEx work we have another ONR grant (ONR-322OM/AOSN: The Development of a Direct Technique for the Determination of Turbulent Fluxes with Autonomous Underwater Vehicles) to perfect our technique of estimating flux from AUV motions, and a grant to test the new technique during the NSF-ONR sponsored program Surface HEat Budget of the Arctic Ocean (SHEBA). SHEBA is focused on determining the surface heat balance of the Arctic Ocean. The vehicle work is germane to SHEBA because as we have found, the ocean fluxes are spatially variable. The only way to account for this variability during the 1997-98 SHEBA field experiment will be for us to use vehicles like the ACTV and the new vehicle we are developing.

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